Numerical Experiments on the Drift Wave-Zonal Flow Paradigm for Nonlinear Saturation*

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The ITG-adiabatic electron (-ae) gyro-landau-fluid simulations of the early 90's [1,2] established that the ExB shear from toroidaly symmetric ($n=0$) "radial modes" provide the dominant nonlinear saturation mechanism for drift wave turbulence. This is loosely referred to as the "drift wave-zonal flow paradigm" for nonlinear saturation [3]. Actually the radial modes (labeled by a radial wave number $k_x \neq 0$) have several components: a residual or zero frequency "zonal flow" part and an oscillatory "geodesic acoustic mode" (GAM) part. The ExB residual flow is nearly in balance with the ion pressure diamagnetic flow [4], hence radial modes have little net fluid flow. The time average residual flow shears result in equilibrium "profile corrugations" near low order rational surfaces [5]. The zonal flows are weakly damped only by ion-ion collisions (which we ignore) and the GAM's are strongly Landau damped only at low to moderate q. At high-q the Hinton-Rosenbluth residual flow [6] vanish and only the GAM's remain. Curiously none of the rich physics of radial modes has been used in nonlinear saturation models which refer only to the linear growth rates of the [$n>0,\ \ k_x=0$] transport producing modes. What is the difference between the residual zonal flow saturation in the low-q (core) and GAM saturation in the high-q (edge)? Do the mechanisms and "paradigm" apply equally well to TEM and ETG turbulence?

To explore these and other questions, we have done "numerical experiments" with GYRO by modifying components of the nonlinear coupling convolution and modifying the linear physics of the radial modes *while keeping the linear physics of the finite-n modes unchanged.* In the latter we modify the "q" in the radial modes to trade off the zonal flows versus the GAMs, modify the "1/R" curvature in the radial modes to vary the GAM frequency, as well as the turn off the radial mode Landau damping. We find: (1) the $[n_1 \neq 0,]$, $[n_2=0]$, $[n=n_1]$ *nonlinear coupling triads* account for nearly all of the nonlinear saturation; (2) the ExB shear ($\delta\phi-$) components of the radial modes nonlinearly stabilize while the diamagnetic ($\delta f-$) components nonlinearly destabilize; (3) transport increases as the zonal flow residuals and GAM damping decrease; (4) transport decreases as the GAM frequency decreases; and (5) the transport is largely unchanged without GAM Landau damping. From contour plots of the time-average nonlinear transfer function [$T(\vec{k}) = -2\gamma_k E(\vec{k})$ with $\sum_k T(\vec{k})=0$], we determine if (6) the radial modes $k_y=0,\ \ k_x \neq 0$ provide a small net sink of turbulent energy $E(\vec{k})$ from GAM Landau damping. Finally contrary to previous work, we find all these mechanisms and "the paradigm" are universal: Conclusions (1-5) hold equally well for ITG-ae, ITG/TEM, and purely TEM transport; and (1-2) appear to hold for ETG transport.

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